Field Repair and Replacement Part Fabrication of Military Components Using Ultrasonic Consolidation Cold Metal Deposition

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ABSTRACT

Timely repair and replacement of military components without degrading material properties offers tremendous opportunities for cost and schedule savings on a number of military platforms. Effective field-based additive manufacturing repair approaches have proven difficult to develop, as conventional additive metal deposition technologies typically include a molten phase transformation and controlled inert deposition environments. The molten stage of laser and electron beam based additive processes unfortunately results in large dimensional and microstructural changes to the component being repaired or re-fabricated. As a result, high residual stresses and unpredictable ductility profiles in the repair area, or the re-fabricated part, make the final product unsafe for redeployment. Specifically, the heat affected zone associated with traditional deposition-based repair methods can produce a low strength, non-homogenous region at the joint; these changes in the materials properties of the repaired parts are detrimental to the fatigue life, and are a major concern where cyclic loading is experienced. The use of solid state high power Ultrasonic Consolidation (UC) technologies avoids the liquid-solid transition complexity and creates a predictable "cold" bond. This method then allows for strong, homogenous structures to be manufactured and repaired in the field and opens the door for the use of high strength repair material that may reduce the frequency of future failure itself. In addition, UC further offers the opportunity to provide enhanced functionality and ruggedness to a component either during repair or from original manufacture by allowing the embedding of passive and functional elements into the new fabricated component or feature.

1.0 BACKGROUND

UC is an additive manufacturing method based on the ultrasonic welding of a sequence of metal foils with periodic material removal through the use of 3 axis computer numerical control (CNC) contour milling. The process was invented, patented and is provided by Solidica Inc., USA [1]. During the process, energy generated from a piezoelectric transducer is transferred to a work piece, through a sonotrode, in the form of ultrasonic oscillation, (typically ~20 kHz), under a compressive normal force (see Figure 1). These oscillations allow metal plastic flow with associated localised deformation and bonding at much lower temperatures than the melting temperature of the foil material (aluminium alloys <150°C, compared to their melting temp of ~600°C), resulting in bonding at the consolidation interface at relatively low pressures (<300 kPa) [2]. This bonding results in true metallurgical bonds being formed between the deposited foil layers. The resultant solid metal object, or metal deposition (and worn feature reconstruction) on an existing object, is then contour milled using the integrated CNC machine at which point the process is continually repeated to obtain the final three-dimensional component. UC is classified as a rapid solid state deposition process and has the following advantages over many other manufacturing processes:

- UC can be used to bond materials that are metallurgically incompatible in fusion processes [3]. (E.g. Al, Ti, Cu, Ni, 316 Stainless Steel, etc).
- UC is energy efficient, consuming as little as 5% of the energy employed for more conventional welding processes [4].
- Due to the low processing temperatures and high degree of low temperature plastic flow UC allows the embedding of temperature and pressure sensitive objects into solid metal matrices. (E.g. SiC fibres, Shape Memory Alloy (SMA) fibres, optical fibres, fibre Bragg gratings, electronic sensors, etc).
- Due to the solid state processing UC has no safety hazards associated with the formation of liquid metal, metal fumes, powder handling, dust or other molten metal handling problems.
- With UC no atmosphere control is required to address molten metal oxidation issues.
- Unlike thermal layer manufacturing methods, UC has greatly reduced residual stresses and net part distortion due to there being no liquid to solid transformation.
- UC deposition rates are higher than for many thermal layer manufacturing processes due to a far larger “deposition spot size” and the lack of any thermal dissipation cycles.

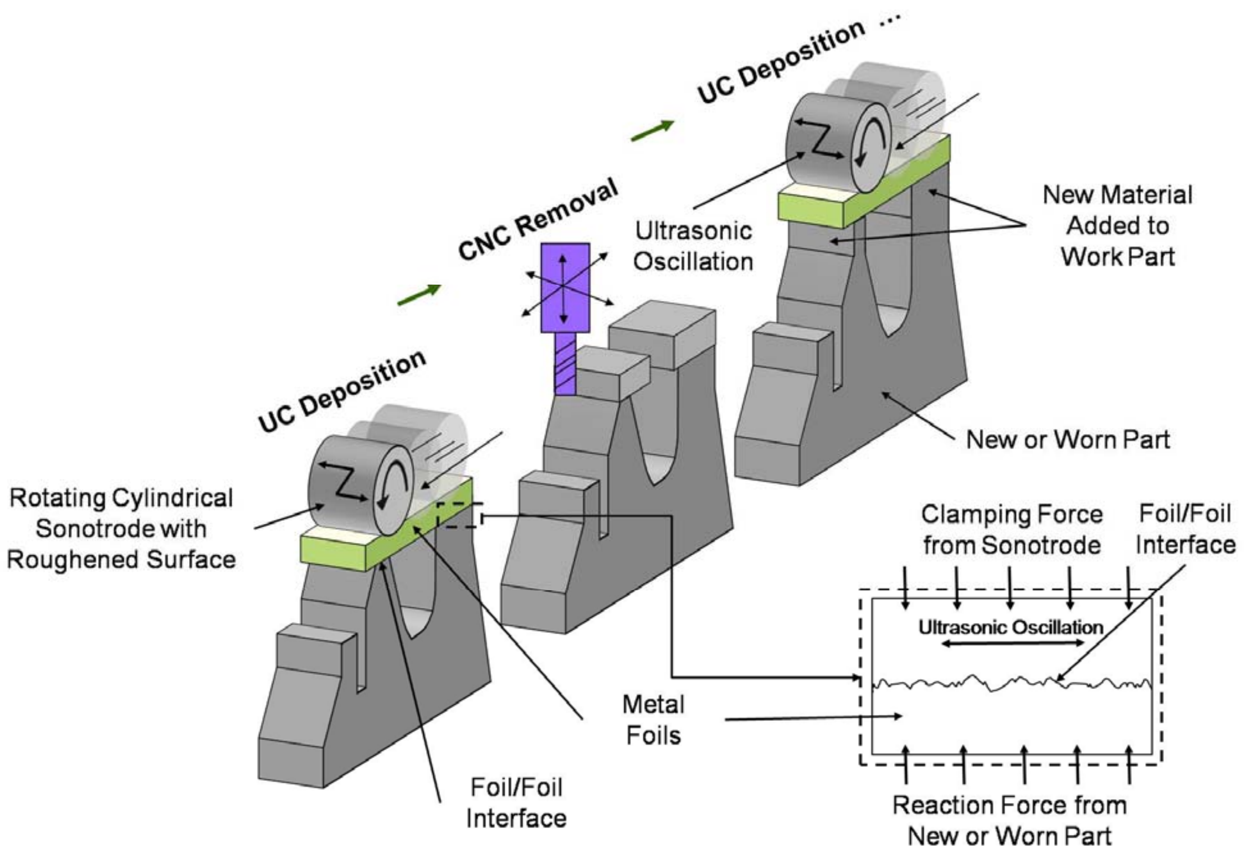

Figure 1 – Schematic diagram of the ultrasonic consolidation process

Figure 1: Schematic diagram of the Ultrasonic Consolidation process

To summarize, UC is a low power, solid state metal layer deposition technology capable of combining many dissimilar materials into single three-dimensional solid objects and is therefore well suited to infield repair and component feature restoration. Further, UC possesses the added benefit of potentially being able to provide additional functionality to standard components through the use of embedded strengthening and/or monitoring elements as part of the repair deposition.

2.0 MAKING COMPONENTS VIA UC

Utilizing UC for the direct fabrication of military components has certain key benefits that are advantageous in this application:

- UC fabricated part's possess excellent geometric accuracy and reproducibility equivalent to those produced using conventional manufacturing techniques
- Replacement components of new designs and materials can be built much faster than conventional production processes, accelerating testing and reducing overall time to deployment.

- Field-based re-fabrication facilities based upon UC would utilise a common build material (rolls of foil), greatly simplifying field logistics.

The proposed UC-based part repair platform would be based upon the successfully implemented commercial Form-ation™ system produced by Solidica [5]. The Form-ation™ platform is a hybrid additive-subtractive automated system for direct manufacturing of components via UC and could be readily modified to accommodate the shapes and sizes of common military components. As shown in Figure 2, the Form-ation™ machine combines a CNC Vertical Machining Centre (VMC) with a UC tape laying subsystem to enable the creation of a wide variety of component geometries. The foil materials most commonly used by Form-ation™ are: Al 3003 TO, Al 3003 H18, Al 1100 TO and Al 6061 TO.

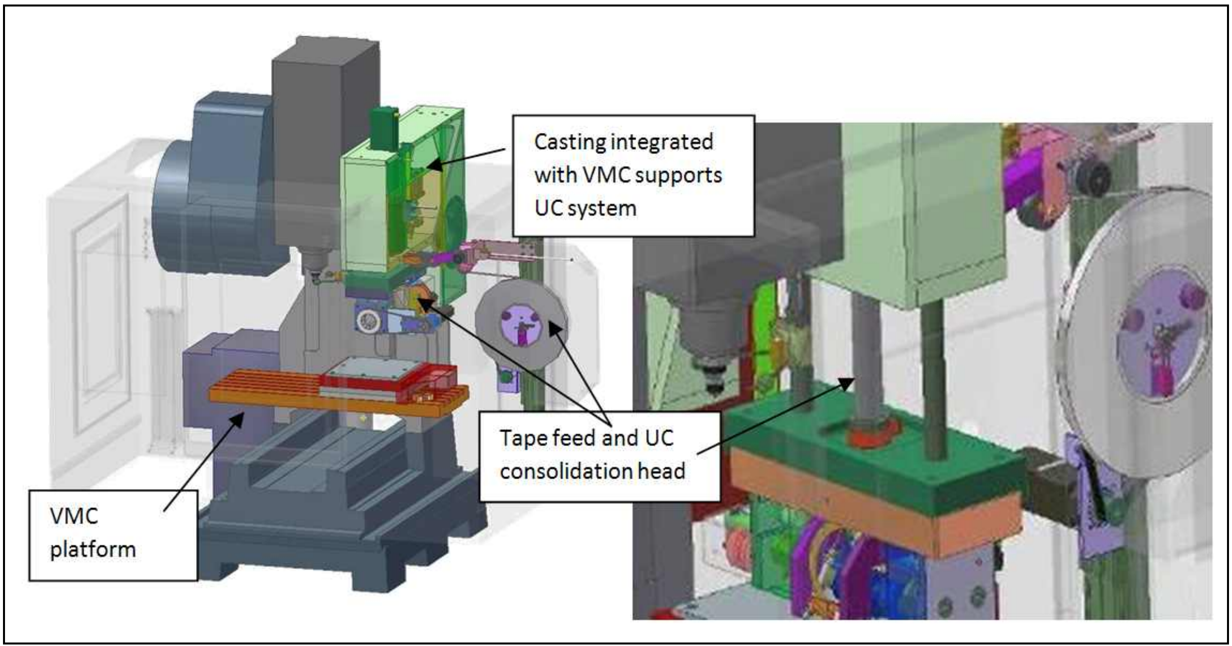

Figure 2: Form-ation™ machine diagram

To produce a desired geometry, Form-ation™ employs a tape approximately 150µm thick and 2.54cm - 30.0cm wide. After each layer of material is deposited, it is trimmed, using a small diameter end mill, and roughly 1mm of excess stock is left on the circumference of the cross section. Depending on the part geometry, this deposition and trimming process continues sequentially to a desired part height, typically 4-8mm of material has been deposited. At this point a finish machining operation is incorporated, providing the final required dimensional accuracy of the part region. The final part possesses excellent net shape accuracy with a high quality machined surface finish. Following this, tape deposition and trimming resumes until the next finish is scheduled. This recurs until the part is completed. Because UC is a solid state process which proceeds at very low temperature, no damage occurs to previously deposited and finished regions as part build proceeds. Residual stresses are also low in comparison to direct metal processes involving liquid-solid transformations, so machining accuracy is maintained.

The result is a finished part with the surface finish and accuracy achievable in conventional milling processes, but with the geometry flexibility of additive manufacturing. In addition this is a one piece flow process;

multiple machining operations (rough cutting, finishing, Electric Discharge Machining (EDM), etc.) are eliminated along with work in process, opportunities for error due to multiple set ups, etc. A figure of the current commercial machine is shown in Figure 3.

Figure 3: Form-ation™ Solidica Ultrasonic Consolidation platform

The United States Marine Corps was recently looking at various options to replace components of the Advanced Amphibious Assault Vehicle in the field; Solidica was selected for a demonstration program to replace one of the control support arms (Al 3003 H18). There was not an available Computer-Aided Design (CAD) model for the control support arms therefore one was reverse engineered in Autodesk® Inventor® 3D mechanical design software and imported into rpCAM™, (rpCAM™ is a graphical user interface for layer-by-layer part builds, to create machining code to recreate a given feature using the Form-ation™ platform), to design the build plan. The Form-ation™ equipment was utilized to build the part out of Al 3003 H18 and ship to the Marine Corps for testing. The part was successfully reverse engineered and fabricated within 24 hours. The process that was followed in this example is noted below.

Receive Part

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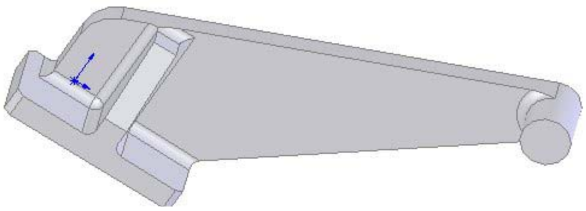

Model Part

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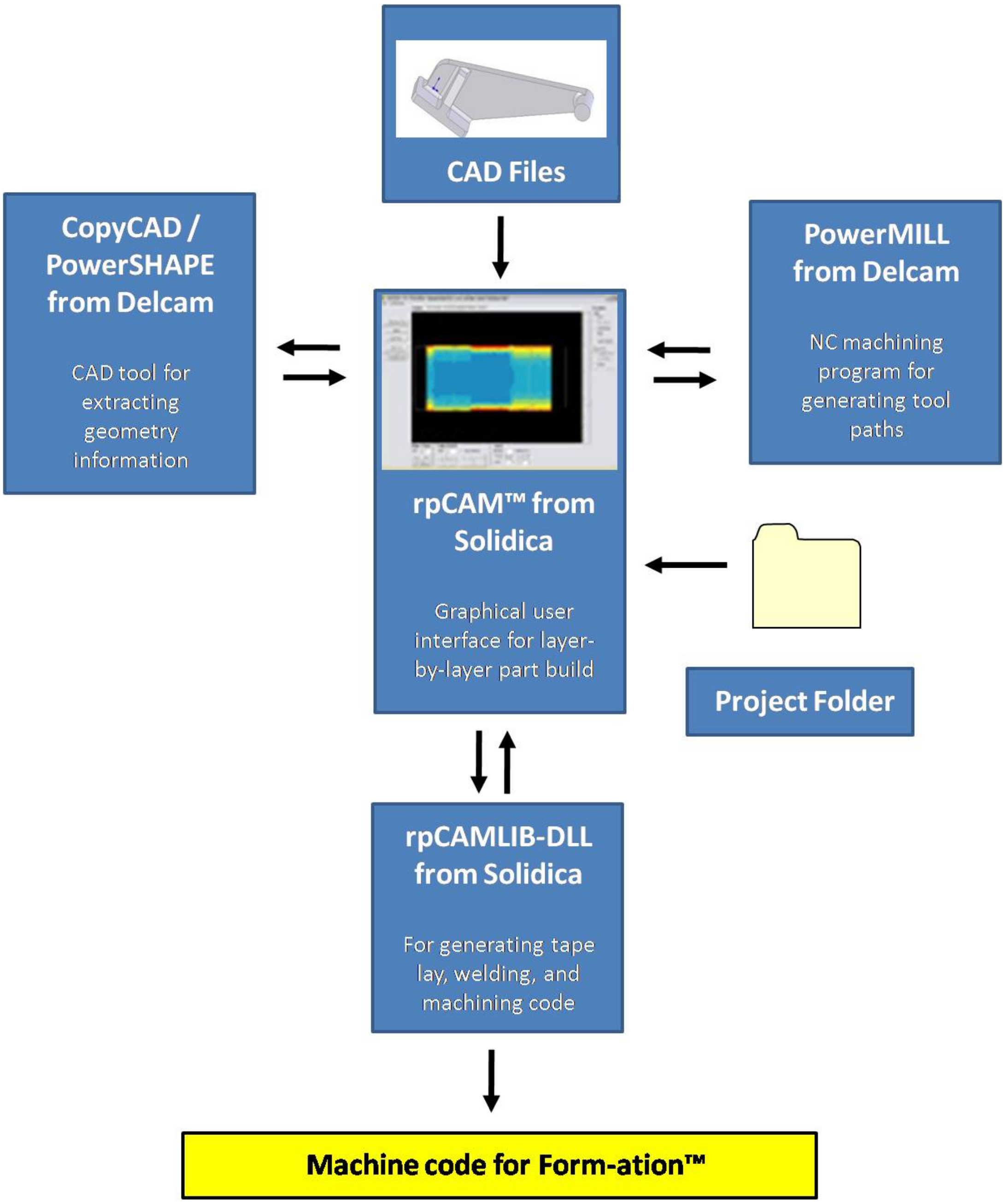

Input Part In rpCAM™

Build Part

Deliver Part to US Marine Corps

3.0 REPAIRING COMPONENTS VIA UC

UC was born as a rapid metal fabrication technology that leveraged the unique benefits of additive manufacturing and solid-state bonding to create unique functional articles but has recently been modified to attempt to address the unique demands of military repair applications, that is, recreating features on existing military components. The Form-ation™ machine discussed previously has been shown to be adaptable to allow for the incorporation of a wide variety of military components within its build volume for direct material deposition once the part to be repaired has been properly fixtured and indexed.

Using standard 2-D or 3-D modelling, military components that have failed can be reverse engineered and then inputted into rpCAM™. Once the machining code is created and the part to be repaired is fixtured and indexed within the machine, the replacement part features can be recreated on the Form-ation™ machine quickly and efficiently. One such example of this is in the case of reapplying the Al 7075 leading edge to a helicopter blade as shown in figure 4. The Al 7075 replacement material will be directly applied to the worn surfaces via UC.

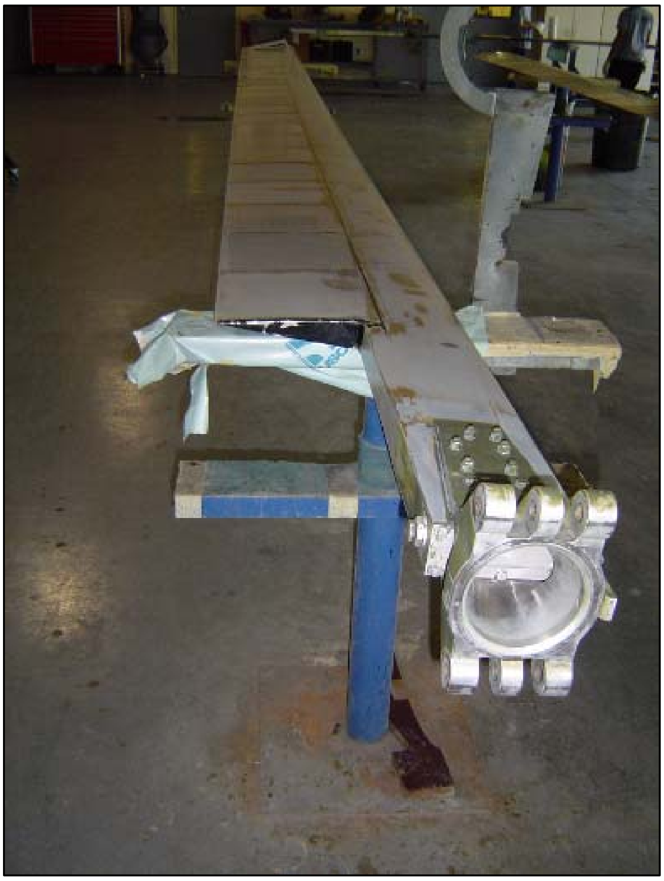

Figure 4: Helicopter blade awaiting leading edge reconstruction

4.0 EMBEDDING OBJECTS VIA UC

UC utilises what is often termed as the "ultrasonic volume softening effect", or "volume effect" to embed objects in a metal matrix material (refer to Figure 5 steps a, b, and c for the embedding process). The volume effect is a less well understood phenomenon, than bonding, in ultrasonic welding (USW) and is sometimes referred to as "acoustic softening" [6]. This effect is characterised by the low temperature, (generally ≤50% of the metals' melting temperature), plastic flow/deformation of a metal material when it is subjected to ultrasonic energy.

The volume effect has been found to occur when ultrasonic excitation energetically interacts, reorients and expands dislocations within a polycrystalline metal. This increase in energy level is found to greatly expand the mobility of the dislocations within the crystal lattice structure of the metal, often forming persistent slip bands within the material that facilitate transient reductions in local Yield Modulus. Another contributing factor is that in metals, grain boundaries, secondary phases and impurities will limit the amount of 'slip' of dislocations within the crystal lattice structure and ultrasonic energy (similar to the effect of thermal energy input) can ease the resistance to dislocation slip; thus reducing the stress needed to deform the metal. This effect in which ultrasonic energy acts as the excitation force for softening the metal material was termed as 'acoustic softening'. The end result of these effects is that volume deformation of metal materials can be performed at lower temperatures using ultrasonic energy than traditional thermal methods of material forming. This volume effect tends to only occur within the weld area of the metal material and greatly facilitates the formation of high density bonds.

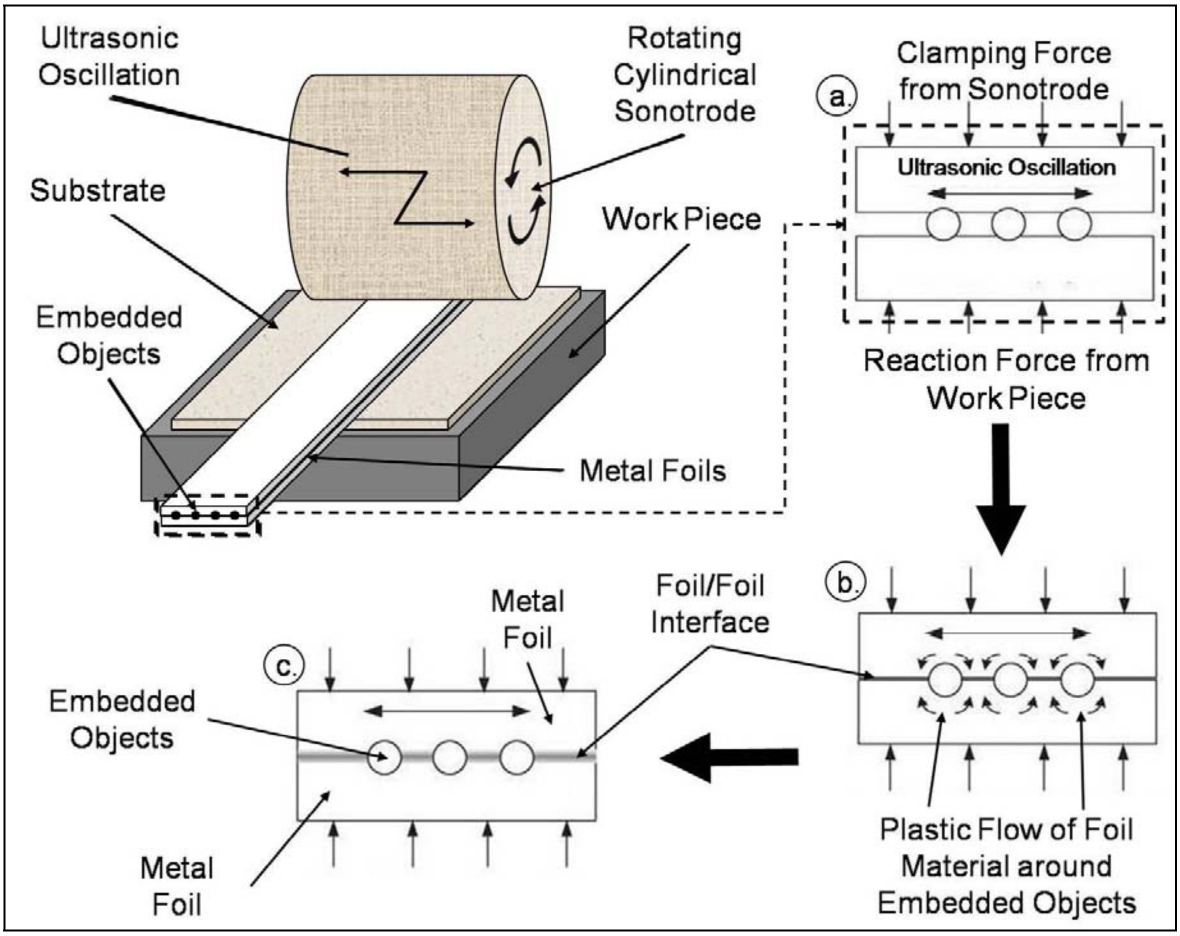

Figure 5: Object embedding via Ultrasonic Consolidation

The volume effect encountered during UC has been exploited by researchers to allow the embedding of optical [7], active [8, 9], and passive fibres [10], as well as various other components [9, 11], within Al matrices while retaining their full functionality. This ability of achieving high plastic flow and high object encapsulation at relatively low pressures and temperatures is a unique property of UC over traditional Metal Matrix Composite (MMC) manufacturing techniques.

A selection of some of the fibre types already embedded via UC is given in Figure 6.

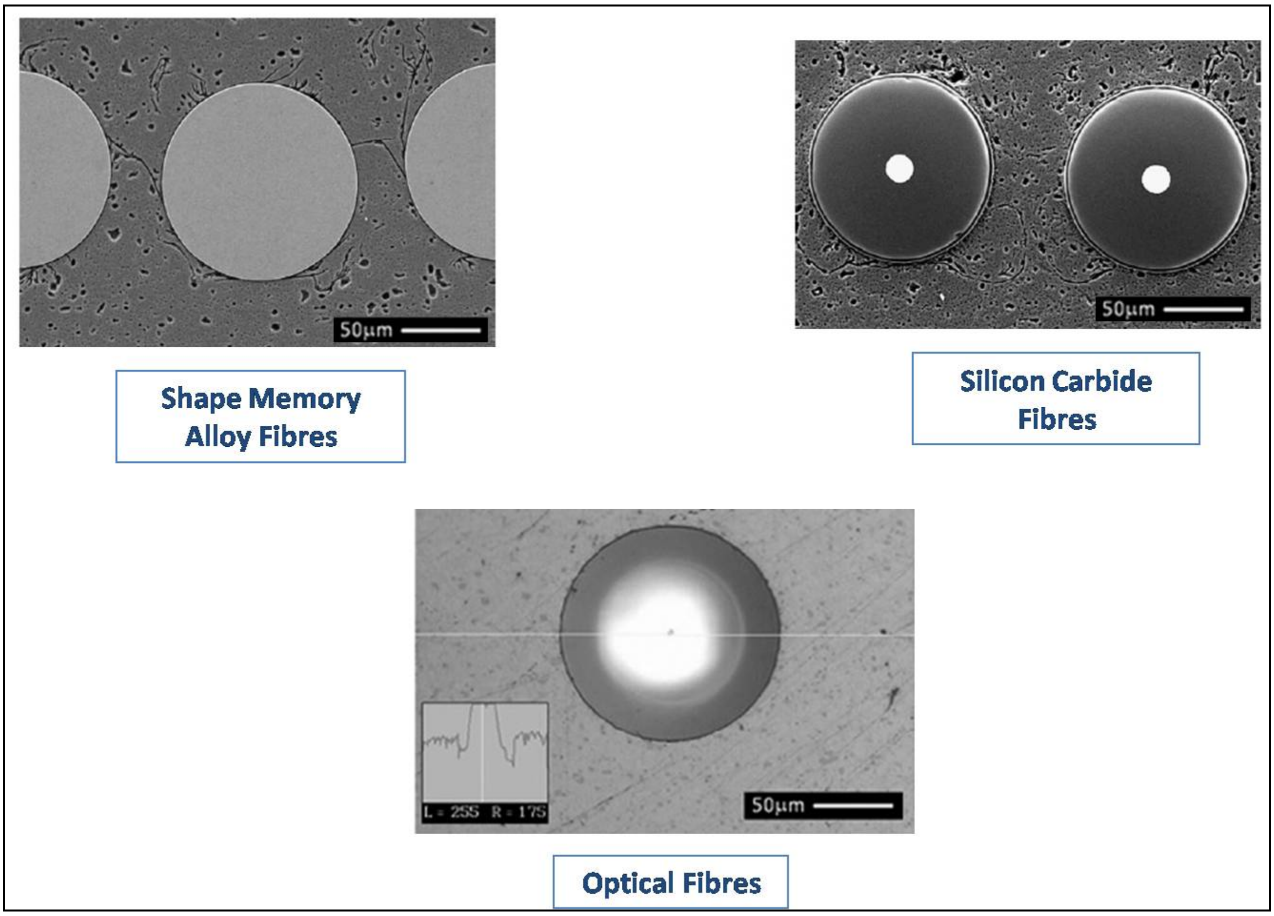

Figure 6: Micrographs of various types of fibres embedded via UC into Aluminium 3003 Matrices

5.0 THE FUTURE

The power of field based repair and part replacement is imperative to the future logistical footprint of the military. Keeping vehicles and military components operational and out of maintenance depots will ultimately lead to long term success for the military. Specific applications, such as feature restoration, damage repair and part replacement, are key areas that UC will be valuable to the future of military repair.

Wear of military components is seen on a regular basis and a high cost for maintenance and survivability. The ability to restore features would decrease both scrap rate and down time while in theatre. Utilizing Formation™ equipment, parts can be mounted and repaired with minimal effort and set up time. The CNC can easily locate and remove material to create a weldable surface. UC will then restore features needed on the component and create a functional part for installation.

Focusing on repairing defects, cracks, and failures in components rather than the entire part has the potential for allowing repairs to happen in a short and efficient time frame. As previously mentioned, UC has the ability to both add and subtract material. Relating to repairs this would allow for a quick turnaround for functionality and full use.

Often time's restoration and repair are not options pertaining to parts on military equipment. In this case utilizing CAD files or reverse engineering components will allow for models to be created, imported and then built directly in short quantities on the Form-ation™ equipment.

In addition to this make and repair mission, UC also has the unique ability to add additional functionality to a component either during repair or from original manufacture. This additional functionality may take several forms (e.g., the use of strengthening fibres in light weight alloys).

To summarize, UC is a rapid metal fabrication technology that leverages the unique benefits of additive manufacturing and solid-state bonding to directly re-create unique functional articles and can be adapted to repair existing worn articles, all within a field-based, expeditionary maintenance environment.

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